Biogeosciences Discuss., 7, 8123–8142, 2010
www.biogeosciences-discuss.net/7/8123/2010/
doi:10.5194/bgd-7-8123-2010

Biogeosciences
Discussions

Near-ubiquity of ice-edge blooms in the Arctic

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Received: 22 September 2010 – Accepted: 26 October 2010 – Published: 4 November 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Ice-edge blooms are significant features of Arctic primary production, yet have received relatively little attention. Here we combine satellite ocean colour and sea-ice data in a pan-Arctic study. Ice-edge blooms occur in all seasonally ice-covered areas and from spring to late summer, being observed in 77–89% of locations for which adequate data exist, and usually peaking within 20 days of ice retreat. They sometimes form long belts along the Ice-edge (greater than 100 km), although smaller structures were also found. The bloom peak is on average more than 1 mg m^{-3}, with major blooms more than 10 mg m^{-3}, and is usually located close to the ice-edge, though not always. Some propagate behind the receding ice-edge over hundreds of kilometres and over several months, while others remain stationary. The strong connection between ice retreat and productivity suggests that the ongoing changes in Arctic sea-ice may have a significant impact on higher trophic levels and local fish stocks.

1 Introduction

The classical picture of Arctic Ice-edge phytoplankton blooms found in the literature – mainly based on cruise transects – is of a long but narrow (20–100 km) band along the ice-edge, moving northward as the ice breaks up and melts over spring and summer (Sakshaug and Skjoldal, 1989). They differ from more traditional open-water blooms with respect to the nature of water column stratification, here induced primarily by freshwater input instead of solar heating. When sea-ice breaks up and melts, there is a freshwater input to the surface that induces strong stratification. Another causal factor is increased solar irradiance at the surface as ice cover shrinks. Since irradiance is typically sufficient by the time ice cover recedes, Sverdrup's (1953) criterion of a mixed layer shallower than the critical depth is met, making the light regime suitable for phytoplankton growth. Ice-edge blooms are generally understood as short-lived phenomena that quickly strip out the nutrients of the shallow (15–35 m) surface mixed layer characteristic of seasonally ice-covered waters (Niebauer, 1991). The area located between the multi-year ice and maximal extent is the seasonal ice cover, which is the subject of this study, with a particular focus on the marginal ice zone (MIZ), which is the region of recent ice melt.

Ice-edge phytoplankton blooms have been detected from cruises in many locations including Bering Sea (Alexander and Niebauer, 1981; Niebauer et al., 1995), Chukchi and Beaufort Seas (Hill et al., 2005; Sukhanova et al., 2009), Canadian Archipelago (Klein et al., 2002; Tremblay et al., 2006), Greenland Sea (Smith et al., 1997), Barents Sea (Luchetta et al., 2000; Hegseth and Sundfjord, 2008), and also in the Southern Ocean (Smith and Nelson, 1985). In the Barents Sea and on the Bering Shelf they are thought to account for 50–65% of annual primary production (Sakshaug, 2004). However, few observations of Ice-edge phytoplankton blooms from satellites have been published to date (Arrigo and van Dijken, 2004), and thus a primary aim of this study is to fill this gap and investigate their existence at the large scale.

It is essential to understand the dynamics of phytoplankton blooms and their future evolution because of their impact on primary production, which in turn affects higher trophic levels (Hunt et al., 2002). Bloom dynamics also play a major role in carbon sequestration and export (Wassmann et al., 2008), and there is considerable uncertainty about the changes they will undergo in response to further ice shrinkage in the next few decades (Sakshaug, 2004; Tremblay and Gagnon, 2009). Satellite observations provide a synoptic-scale picture of these blooms, necessary for the development of a theoretical understanding that will permit their future forecasting.

2 Sources of satellite data

Chlorophyll concentrations are obtained from Level 3, daily SeaWiFS ocean colour data[1] derived using the OC4v4 empirical algorithm, and are provided on a Cartesian,

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[1] http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Daily/chlor/

1/12° grid. Sea-ice concentrations are obtained from National Snow and Ice Data Center (NSIDC), and are based on daily passive microwave radiometry with the Bootstrap algorithm (Comiso, 1999). Sea-ice fields are provided on a polar stereographic grid, at 25 km resolution; here we interpolate them onto the chlorophyll grid using a nearest neighbor scheme (sensitivity tests find that the type of interpolation applied has little influence on the results; results not shown). The SeaWiFS and NSIDC datasets both cover the period 1998–2007.

Following Pabi et al. (2008), we set the boundary between sea-ice and open-water as a sea-ice concentration of 10%. This value is considered reliable for this type of measurement (Worby and Comiso, 2004), and this threshold approximately corresponds to the value above which ocean colour data are flagged as contaminated by sea-ice and chlorophyll values are therefore unavailable.

We define the MIZ as the region for which ice concentration is reduced to consistently less than 10% within the last 20 days (Fig. 1). The temporal coverage of ocean colour sensors is poor at high latitudes with gaps that can last for several weeks, especially during the ice-melt period. There is an average of five observations per pixel in these first 20 days. This relatively poor coverage is in part the result of heavy fog that forms at this time of the year as relatively warm water is exposed to the colder atmosphere. This phenomenon adds to the effect of clouds and ice on masking the sea surface. Even when available, the quality of ocean colour data may be further affected by sea-ice present at the subpixel scale (Bélanger et al., 2007) and by Coloured Dissolved Organic Material (CDOM) that is abundant in Arctic waters. The globally-calibrated, empirical algorithm OC4v4 may therefore include large errors in chlorophyll retrieval (Cota et al., 2004; Gregg and Casey, 2004). Those deficiencies are however not critical to this study of blooms, since the biases are consistent in time and space and thus relative changes are meaningful. Moreover, a high precision in the measurements is largely irrelevant in much of the anaylsys conducted here, since blooms are readily identified by order of magnitude changes.

Some aspects of this work however involve quantitative analysis that is more sensitive to quality of chlorophyll data and requires a closer inspection. The problem of subpixel contamination by sea-ice has been recently addressed in the literature (Bélanger et al., 2007) and suggests that chlorophyll may be overestimated at moderate to high concentration (>0.5 mg^{-3}), and underestimated at low concentration (0.05 mg m^{-3}). This effect is amplified by the presence of CDOM. Bélanger et al. (2007) report however that only a small fraction of pixels are affected. A chlorophyll threshold of 0.5 mg m^{-3} has been defined in our work to identify the blooms (see next sections), based on visual observation and knowledge of bloom dynamics. It is worth noting that this chlorophyll level is least affected by subpixel contamination, and is therefore well suited to discriminate between background chlorophyll concentration and blooming conditions. Automatic flagging of pixels during the processing of water-leaving radiance may fail to detect such contamination (Bélanger et al., 2007), but comparison with another chlorophyll dataset (MODIS) indicates that detection of subpixel contamination and more generally retrieval of chlorophyll in Arctic water varies between sensors. Visual inspection (not shown) reveals indeed that at certain locations and times SeaWiFS data may present a noisy aspect (likely the effect described above) while this is not the case for MODIS, which is smoother and has in general lower chlorophyll values. MODIS has however a very poor coverage in the Arcic (twice as few observations than SeaWiFS in the MIZ on average, not shown), which is possibly a drawback for using stricter quality control. MODIS data are used in this study to provide an independant, conservative estimate for bloom occurrence, recognizing that the lack of valid data in MODIS is a strong bias toward underestimation. The spurious effect of CDOM was further addressed by excluding coastal areas of the analysis.

3 Illustrative examples

This section describes major Ice-edge phytoplankton blooms in various regions, providing an overview of their diversity in shape, intensity and timing. All images shown in this section are 5-day composites to overcome data gaps.

The Barents Sea is one of the most studied regions regarding Ice-edge phytoplankton blooms, lying between Norway and the Svalbard archipelago. An early bloom occurred in 1998 at the southernmost edge of the ice (71–75°N) that propagated over ~100 km in a month (Fig. 2a). Figure 2b shows a bloom occurring in 2000, much further north at 80°N and three and a half months later. These illustrate the length of the melt season and size of the seasonal ice cover in this region. Here major blooms (>4 mg m^{-3}) are not seen propagating over the whole region, but are rather manifested as transient local increases in chlorophyll. Smaller blooms usually propagate over greater distances, following the classical view depicted by Sakshaug and Skjoldal (1989). Most blooms form a band of usually less than 100 km width, with chlorophyll values near the ice edge distinctly greater than in post-bloom conditions (<0.4 mg m^{-3}).

The Chukchi Sea (Fig. 2c) in the Pacific sector presents the same type of ice retreat northwards, but the northernmost Ice-edge is now at 72° N, the same latitude as the southern Barents Sea. Here (23 July 2004) blooms occur all along the Ice-edge in a very long band, forming a circular arc that grows as the ice melts further away, leaving behind post-bloom conditions with very low surface chlorophyll concentration. The Bering Strait, visible at the south of the region, has continuous blooms due to inflow of high-nutrient waters (Sakshaug, 2004). High values along the coast should be viewed with caution since these waters are likely to be contaminated by CDOM from rivers.

Sea-ice retreat is not always northward, as exemplified in the region west of Greenland: Baffin Bay and Davis Strait (Figs. 2d–e). The composites are 20 days apart and show the course of the ice retreat, shrinking both westward from Greenland and south-eastward from the north. The ice remains in the middle of the bay before melting completely, leaving behind a trace of chlorophyll, a sign of the Ice-edge bloom's presence. The Ice-edge blooms thus follow the retreating sea-ice whatever its direction of propagation, indicating the strength of the biophysical coupling with sea-ice.

4 A bloom in motion

One of the main characteristics of an Ice-edge bloom is its local transience and its wave-like propagation, sometimes over great distances, as illustrated by three 5-day composites at intervals of 10 days (Figs. 3a–c). This massive bloom was observed off the west coast of Greenland and started some time before the sequence when the sea-ice broke up, before disappearing shortly afterwards. The peak of the bloom is located near but outside the 10% ice contour, which makes it easily observable from satellite. Low chlorophyll values are visible between the main patch of the bloom and the sea-ice. The bloom is clearly propagating in a 20–100 km belt behind the retreating ice edge.

A Hovmöller diagram (Fig. 3d) shows the evolution of the bloom at 69° N, based on daily chlorophyll and sea-ice data. The bloom lifetime does not exceed 20 days locally but over its whole course its duration is of the order of 2–3 months. The uncertainty regarding its duration comes both from the missing data between days 190 and 215, and from the choice of a chlorophyll threshold to define the bloom. Indeed, although the bloom clearly weakens as it moves westward, the chlorophyll values in the vicinity of the ice edge remain above a level of 0.5 mg m^{-3}, before finally decreasing to an open-water background value after a few weeks. The exception is near the coast where chlorophyll remains moderately high all the year round (though, again, this may be confounded by CDOM contamination). The bloom starts approximately at the time when the ice concentration falls below 10%, though the combined effect of sea-ice and clouds means that the first valid pixel often coincides with a bloom situation (concentration >0.5 mg m^{-3}) as observed on vertical sections of the Hovmöller diagram. On the eastern side (54–56° W) there is a larger lag between ice retreat and blooms, making the classification as to whether open ocean or Ice-edge bloom unclear. Such delayed blooms principally occur when the Ice-edge retreat has stagnated. A more typical Ice-edge bloom then develops once the retreat recommences.

5 Synthetic view of the blooms at the pan-Arctic level

The transient aspect of Ice-edge blooms and their timing, strongly related to sea-ice melt, make them difficult to detect in monthly averages of satellite data. An alternative approach consists in producing a composite figure in which each pixel corresponds to the MIZ period locally, independent of its neighbors (Arrigo et al., 2008; Pabi et al., 2008). Such a composite can span a period of several months. In practical terms for this study, Ice-edge blooms have been assumed to occur up to 20 days after ice concentration becomes durably less than 10% (no new growth of sea-ice or import of drifting ice until the end of the season). Figure 4a shows the timing of the first ice-free day in that sense, for 2007, and this is used subsequently to delimit the MIZ period. Features such as ice-retreat path and overall ice-melt timing for all regions of the Arctic are visible.

Figure 4b shows the chlorophyll level at the peak of the transient Ice-edge bloom. Again, high coastal values on the Eurasian and western Canadian shelves are regarded cautiously due to significant riverine inputs with high CDOM loading. It is noticeable that blooms are almost ubiquitous in the Arctic. In particular, Baffin Bay and the whole Canadian Archipelago, Barents Sea, Greenland Sea, Beaufort and Chukchi Sea, as well as the Russian Seas commonly experience strong (1–10 $\mathrm{mg\,m^{-3}}$) blooms. Taking the mean or median of the chlorophyll levels during the MIZ period smoothes the picture but does not change it qualitatively, nor does the choice of a 15- or 20-day MIZ period.

Missing data is a major issue with remote sensing in high latitudes, especially for Ice-edge blooms. Even with clear sky conditions, partial sea-ice cover (where a remotely sensed pixel contains both open water and sea-ice) may hide the first phase of the bloom or sometimes its peak, leading to underestimation. The impact of sea-ice is difficult to assess without in situ data, but clouds or fog can be monitored by noting the number of valid chlorophyll data points in the MIZ period (Fig. 4c). In this way it is found that around half of the pixels have at least 3 observations during the MIZ period and allow detection of the blooms. However, poor coverage, such as in the high Arctic (150–210° E) or in central Baffin Bay, coincides with areas of apparently lower peak chlorophyll concentration. This often corresponds to cases where the first valid data arrive almost at the end of the MIZ period as defined above, and therefore find post-bloom conditions. This underlines a limitation of satellite data in that the apparent absence of a bloom does not mean that one did not occur.

The frequency of occurrence of ice edge blooms in 2007 is quantified in Fig. 5a. The melt season spans from day 60 in the Atlantic sector to day 250 at high latitudes (see Fig. 4a), with the majority of the melting occurring from June onwards. To identify an Ice-edge bloom, we require a minimum of 3 valid chlorophyll observations within the MIZ period, and that at least one exceeds a bloom threshold of $0.5\,\mathrm{mg\,m^{-3}}$. Moreover, we apply a coastal mask to diminish the impact of CDOM contamination. Of those points adequately observed, 89% fulfil the latter criterion. If instead of SeaWiFS, the MODIS sensor is used a more conservative value of 77% is found, due to a combined effect of often lower chlorophyll values and less data coverage (see section 2). For ∼30% of points with recorded blooms the first observation is the highest, indicating that the bloom probably peaked before the ice concentration durably reduced to below 10%, while a further 52% show the chlorophyll peaking in the MIZ period. The remainder have values increasing still after the end of the MIZ and may be due to slow development, to becoming part of an open-water bloom, to being downstream of the Bering Strait (which has high productivity year round) or to CDOM contamination (most likely in the Russian seas). Indeed, nearly half the blooms have terminated (decreased below $0.5\,\mathrm{mg\,m^{-3}}$) within the MIZ period. The above values are averages over the whole year, but separation into different melt periods (Fig. 5b) shows pre-melt blooms are uncommon early on (insufficient light) and late-peak blooms rare after day 230, when growth conditions are propitious and the period ice-free may be only 20 days.

We now consider primary productivity in the Arctic basin, and the contribution made by initial Ice-edge blooms. No models of primary production are well-validated in this region, so we use a simple one, the vertically generalised production model (VGPM), for illustrative purposes, noting that the resulting estimates have considerable uncertainty. The VGPM calculates the production of organic matter based on chlorophyll, temperature, photosynthetically available radiation and day length (Behrenfeld and Falkowski, 1997). Figure 6a shows the resulting total primary production for the seasonally-covered ice region for 2007. Unsurprisingly, production is greatest in coastal waters and more southerly areas where the ice-free period is of greatest duration. To estimate the importance of Ice-edge blooms, Fig. 6b shows the ratio of mean production rate in the first 20 days after ice retreat to that in the remainder of the ice-free period. At higher latitudes, close to the permanent sea-ice, the MIZ period is more productive, often significantly so, although with considerable variability. One source of this variability is the date on which ice cover is first lost, and the duration of ice-free conditions. One caveat is that phytoplankton are much higher in the water column during the Ice-edge bloom than for subsequent open-water blooms, which may affect productivity rates.

6 Conclusions and perspectives

Satellite ocean colour sensors are the only instruments to provide a synoptic-scale view of Ice-edge phytoplankton blooms and their motion following the receding ice edge. Although noted in a number of hydrographic surveys, their occurrence has never before been properly quantified. However, even satellites suffer from gaps in the data record due to clouds, fog and (more intrinsically) sea-ice. Of points becoming durably ice-free only ~50% have at least 3 observations in the succeeding 20 days, but 89% of these cases showed a bloom in that period. This value carries some uncertainty due to limitations of remote-sensing in the Arctic, but another sensor with different chlorophyll retrieval algorithm and less data coverage still yields a very high occurence frequency of 77%. A greater occurrence of blooms may be masked by the long data gaps in the MIZ period. For half of the points showing such a bloom, it terminates within 20 days indicating the rapid response needed by those wishing to sample it directly. For regions of early ice melt, MIZ blooms are less common, and their contribution to annual primary productivity is diminished by the long periods available for open-water blooms. However, at high latitudes mean productivity rates during the MIZ period may be 1.5–2 times greater than those in open-water conditions.

Understanding Ice-edge blooms and their timing is valuable to identify links with higher trophic levels and, eventually, fish stocks. For instance, Hunt et al. (2002) showed that either top-down or bottom-up regimes can exist in the southern Bering Sea, depending on the timing of ice-retreat and therefore blooming. Water temperature at the time of the bloom may limit or favor zooplankton larvae growth and survival. In Hunt et al. (2002), late ice-melt was related to early blooming while early melt found late blooms. In our study, blooms closely follow ice retreat leading to a more direct relationship. The implication of inter-annual changes in the timing of this retreat for fish recruitment needs further investigation.

Changes in ice melt driven by anthropogenic climate change may lead to a seasonally ice-free Arctic Ocean, with substantially different heat and freshwater budgets and stratification (Serreze et al., 2007). This could lead to Ice-edge blooms propagating over much greater distances as the melt season becomes longer. Whether these blooms become more intense and prolonged and ultimately increase total Arctic primary production will depend on the fate of the Arctic halocline that currently isolates the surface euphotic layer from the deep nutrient pool. The balance between projected increased riverine input (Peterson et al., 2002), modified ice transport (Serreze et al., 2007), increase in storms (Yang et al., 2004) and internal waves eroding the halocline (Rainville and Woodgate, 2009) will determine the future characteristics of blooms and primary production in the Arctic Ocean.

Acknowledgements. We are grateful to the NSIDC for the provision of ice concentration data, to NASA Goddard Space Flight Centre for the SeaWiFS and MODIS chlorophyll data, and to Stephanie Henson for coding the VGPM.

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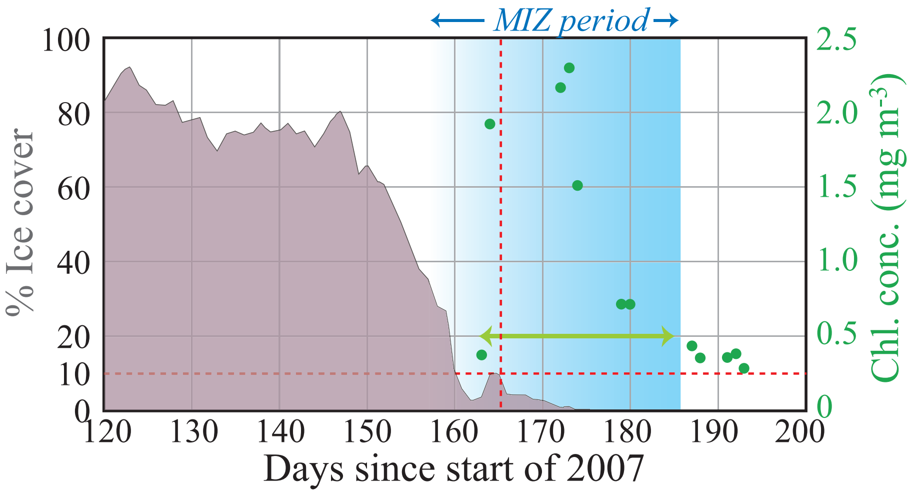

Fig. 1. Illustration of data coverage for an example location in Baffin Bay, showing our definition of the MIZ period and the existence of an Ice-edge bloom. Our MIZ period is up to 20 days after sea-ice concentration is durably below 10%, and a bloom is registered when chlorophyll concentration exceeds 0.5 mg m^{-3}.

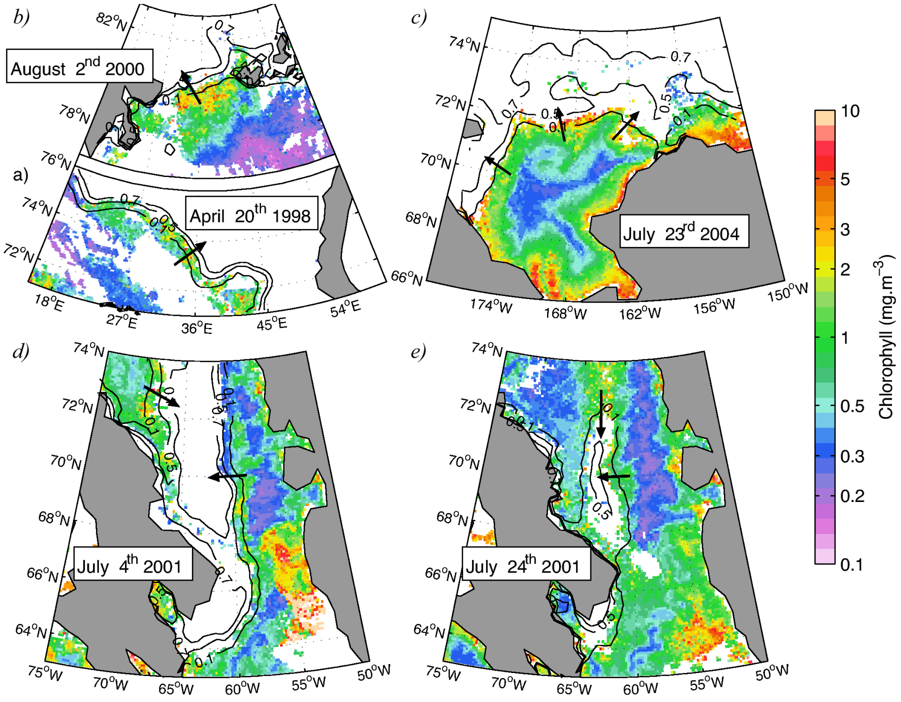

Fig. 2. Examples of Ice-edge phytoplankton blooms and their evolution in different marginal seas of the Arctic. Barents Sea in **(a)** April 1998 (71–75° N) and **(b)** August 2000 (79–81° N). **(c)** Chukchi Sea in July 2004. **(d, e)** Davis Strait and Baffin Bay in July 2001 showing the change that occurs in 20 days. All images are 5-day composites of chlorophyll (SeaWiFS) overlaid with sea-ice contours (NSIDC) at 10%, 50% and 70%. White areas are missing chlorophyll data. Arrows indicate the propagation direction of the ice-edge, and hence of the blooms.

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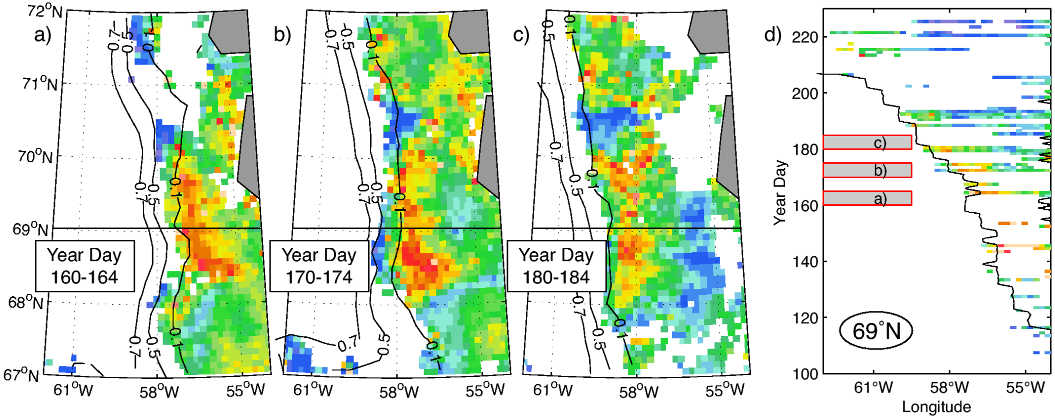

Fig. 3. An example of the propagation of an Ice-edge phytoplankton bloom west of Greenland over a 25-day period, **(a, b, c)**. The three images are 5-day composites of chlorophyll (SeaWiFS) overlaid with sea-ice contours (NSIDC) at 10%, 50% and 70%. White areas are missing chlorophyll data. Panel **(d)** shows a corresponding Hovmöller diagram at 69° N that illustrates the progression of the 2007 bloom, and shows that this can be followed for many months despite large data gaps.

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Interactive Discussion

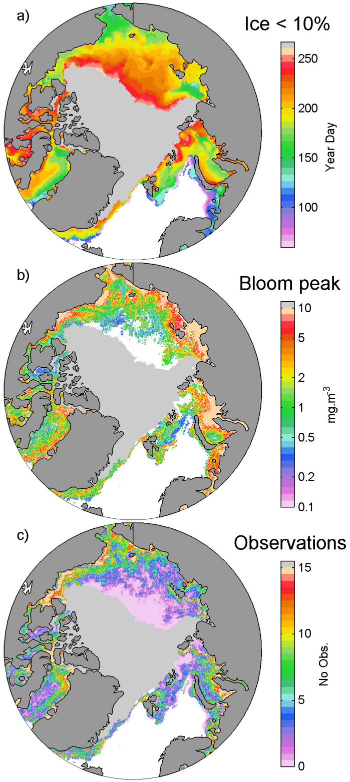

Fig. 4. Summary statistics for whole Arctic during 2007. In all geographical panels, light grey areas correspond to permanent sea-ice cover, and white areas to open-ocean or missing data. **(a)** First day of the year that is durably ice-free. **(b)** Maximum chlorophyll concentration attained within the moving MIZ. **(c)** Number of valid SeaWiFS chlorophyll observations within the MIZ.

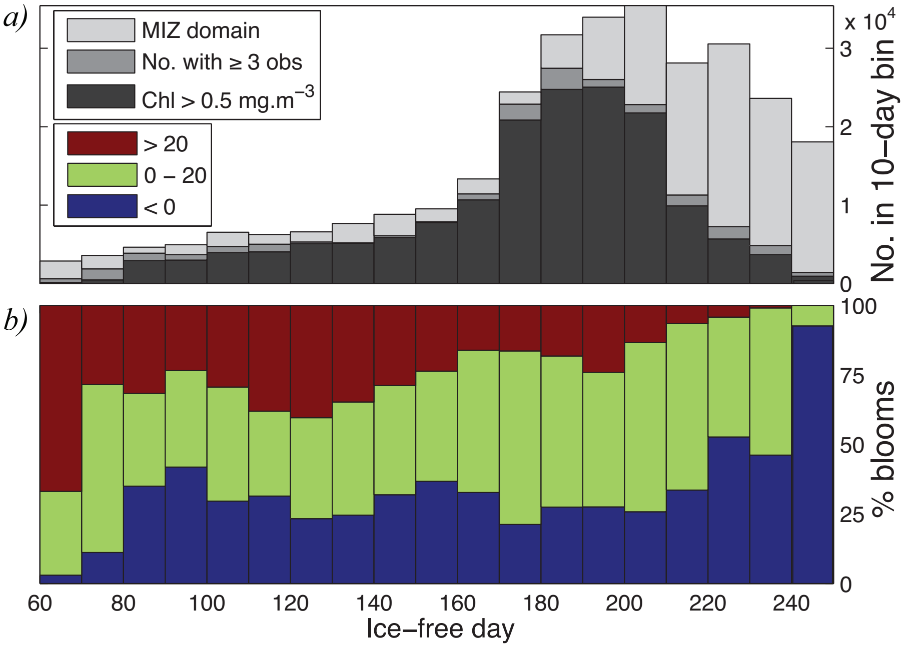

Fig. 5. Summary statistics for whole Arctic during 2007. **(a)** Number of MIZ pixels that become ice-free on a given day (light grey); pixels with more than 3 valid chlorophyll observations (dark grey); and those classified as a bloom (black). **(b)** For adequately observed blooms in MIZ, the percentage of them showing peak occurring before durably ice-free (<10%) conditions (blue); within 0–20 days of melt period (green); or later (red).

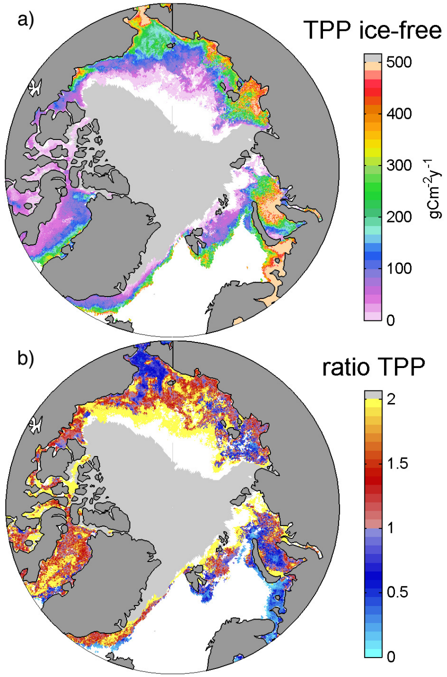

Fig. 6. Summary statistics for whole Arctic during 2007. **(a)** Total vertically-integrated primary production for the seasonal ice zone for the full year. **(b)** Ratio of average production rate in MIZ period to that for the rest of the ice-free period. Warmer colours (red-yellow) indicate regions where the MIZ exhibits higher rates of productivity than the rest of the year. In both panels, light grey areas correspond to permanent sea-ice cover, and white areas to open-ocean or missing data.